Neutrinos Past ,Present and Future

or

The Neutrino Odyssey

Outline of the Neutrino story

Elementary Particles

High Energy Physics and Einstein

The Birth of the Neutrino

Neutrino Observation

More neutrinos...

Neutrino Mysteries

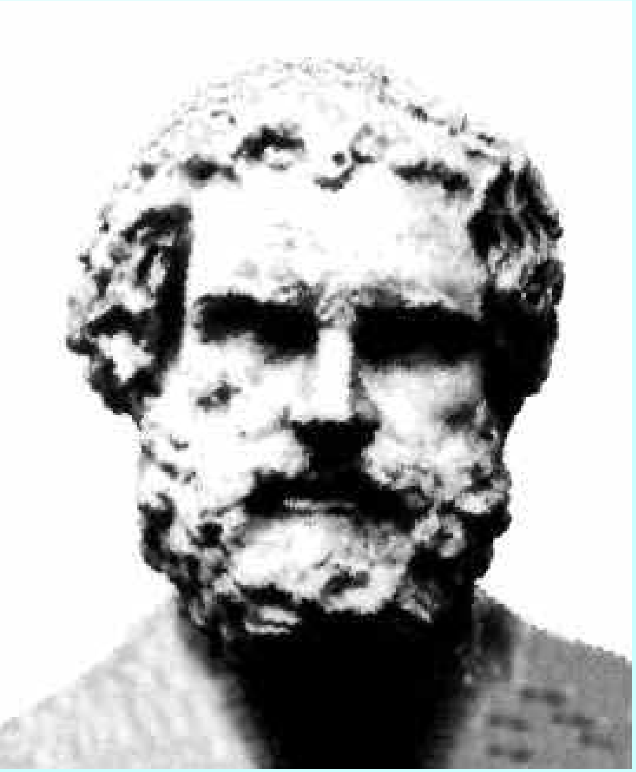
Neutrino Identity Crisis

What we already know, learn as we speak, and hope to learn in the future

Fundamental Particles...

• Fundamental or Elementary particle in High Energy Physics language : An entity (particle) that (as far as we know) has no inner substructure.

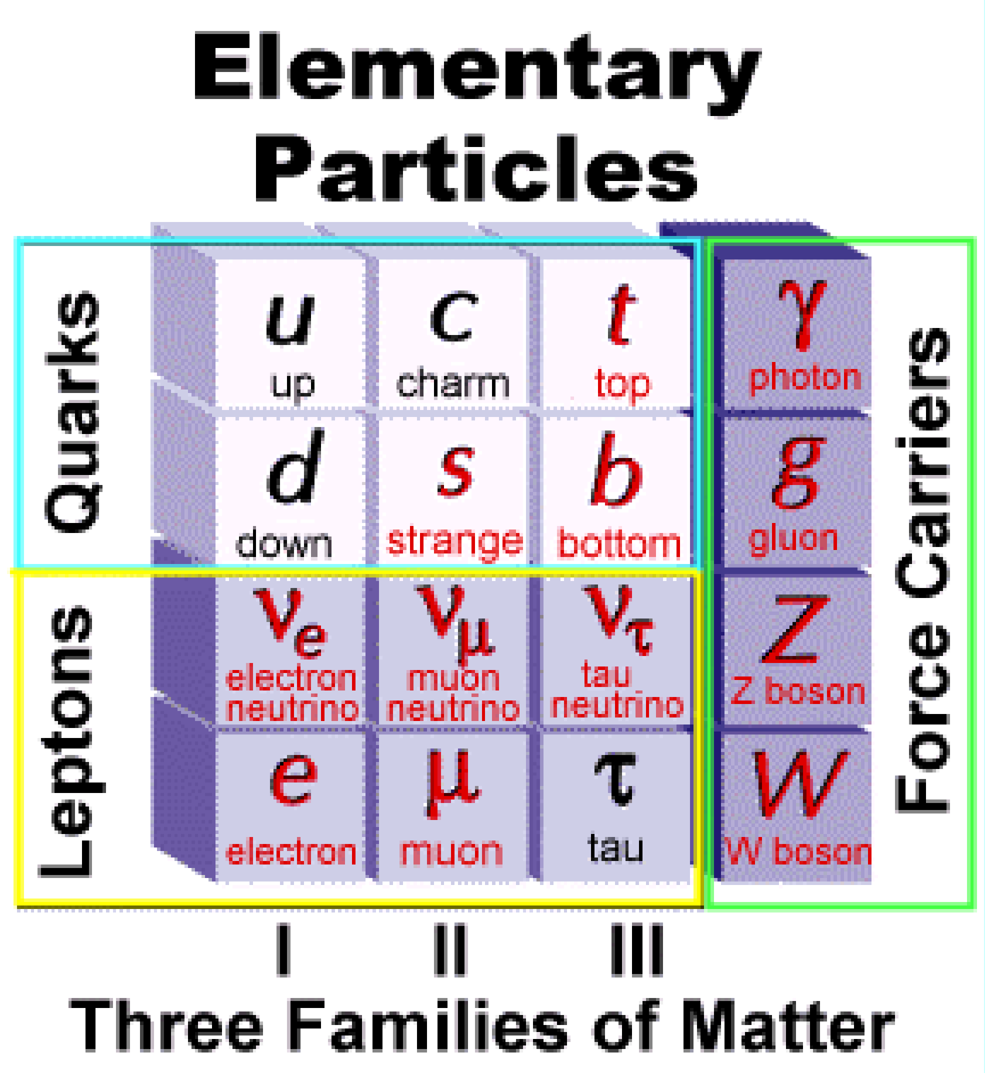
• Idea of the existence of fundamental particles that are the building blocks of matter is thousands of years old :



Greek Philosopher Democritus (460 BC) introduced it first, and the word he used to describe them, "Atom" in Greek means "the one that cannot be divided into smaller pieces".

Fundamental Particles 2500 years later

- There are 12 elementary particles (and 12 anti-particles) and 4 force carriers



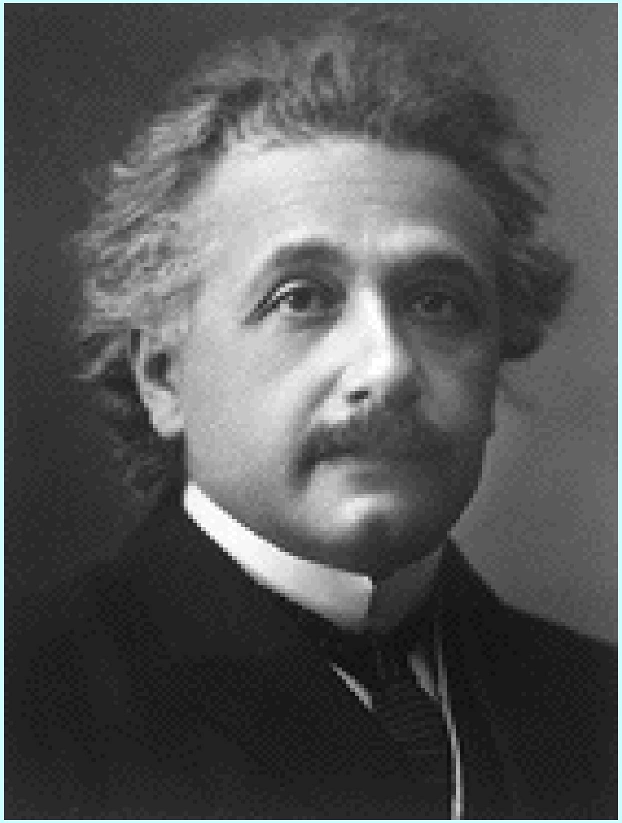
High (as opposed to Low) Energy Physics…and Einstein

- High Energy Physics is the section of Physics that studies particles moving with speeds much higher than what we are accustomed in every day life : they move with speeds very close to the speed of light,c.

c = 300000000 m/sec

Einstein's Special Theory of Relativity describes the motion of particles moving at speeds close to the speed of light. It gives the correct laws of motion (mathematical equations) for any particle.

Many years of high energy physics experiments have thoroughly tested Einstein's theory and shown that it fits all results to date.

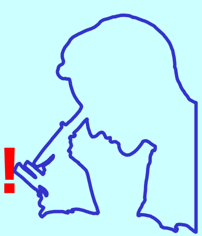


Nobel Prize in Physics 1921

Special Relativity and High Energy Physics : a characteristic example

MUONS EXPECT (CALCULATED) TO SEE AT THE SEA LEVEL IN 1 HOUR : 27

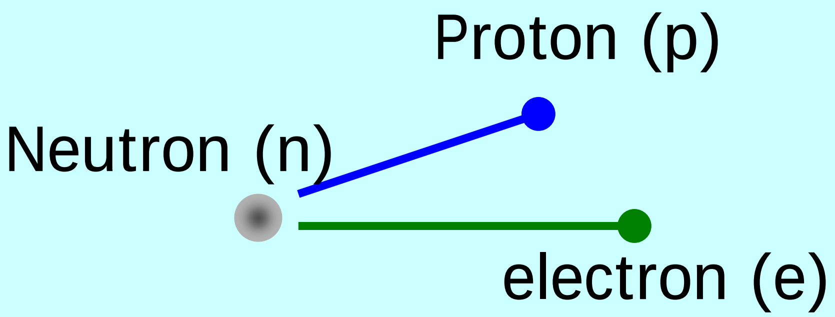
MUONS IN 1 HOUR : 412 !!!



What did we do wrong??? Nothing apart from the fact that we did not use Einstein's equation of Special Relativity for Time Dilation. If we do then what we expect and what we observe agree very very well.

Energy “non conservation” and the Birth of the Neutrino

- In 1930 a big crisis appeared in the High Energy Physics community :

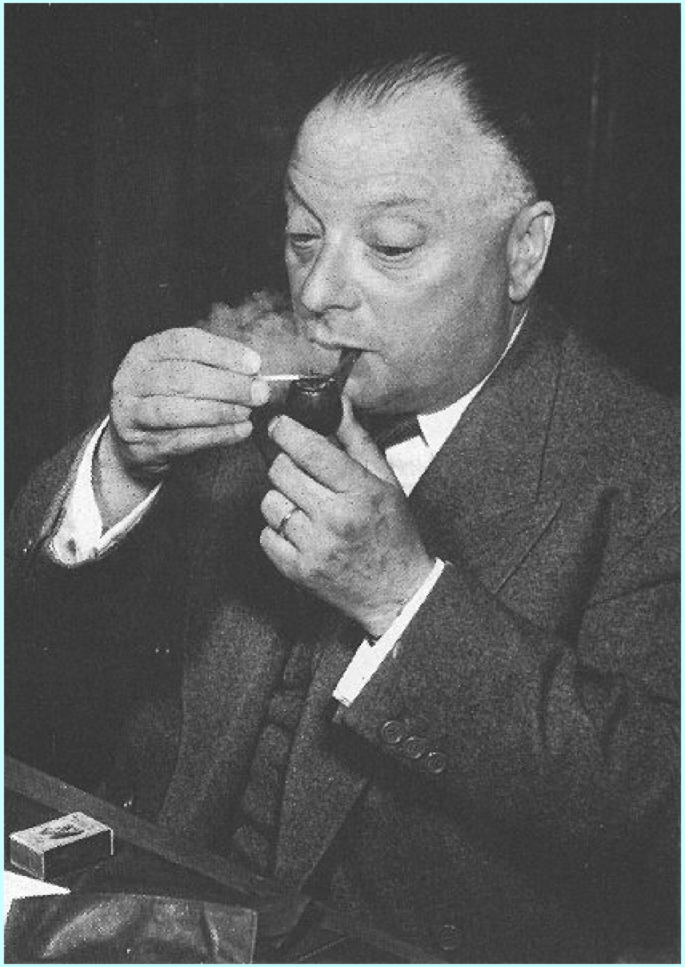


LAW OF CONSERVATION OF ENERGY

ENERGY BEFORE ?= ENERGY AFTER

- Austrian theorist W. Paulі came up with a “crazy idea” for the existence of a new particle for which he confessed :

”I have done something very bad today in proposing a particle that cannot be detected. It is something no theorist should ever do”.



Nobel Prize in Physics 1945

Letter by Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those particles very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
. W. Pauli

Baptism of the Neutrino and the Theory of weak interactions

- **In 1933 Italian theorist and experimentalist Enrico Fermi (Fermi-Lab), calls the particle invented by Pauli " neutrino " which in Italian means "the little neutral one".**

- He also formulates the so called "theory of weak interactions" in which neutrinos find a natural place to be.

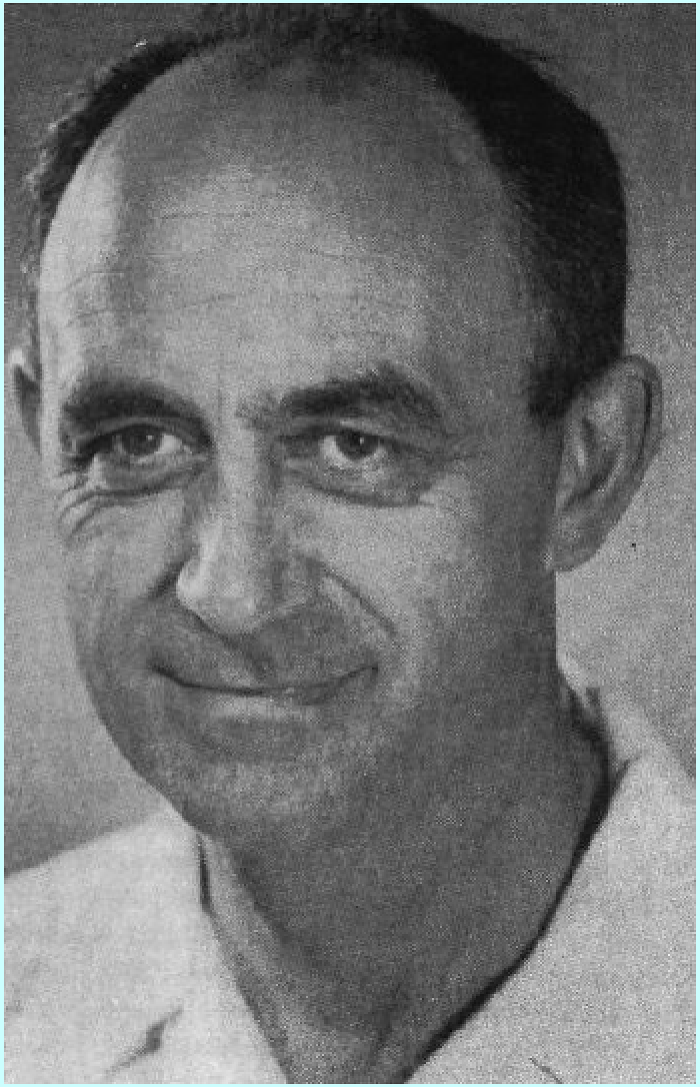
- However, with neutrinos being

  a) Neutral

  b) With nearly (or exactly) zero mass

  c) Interacting weakly (probability of "doing something" with matter extremely small!)

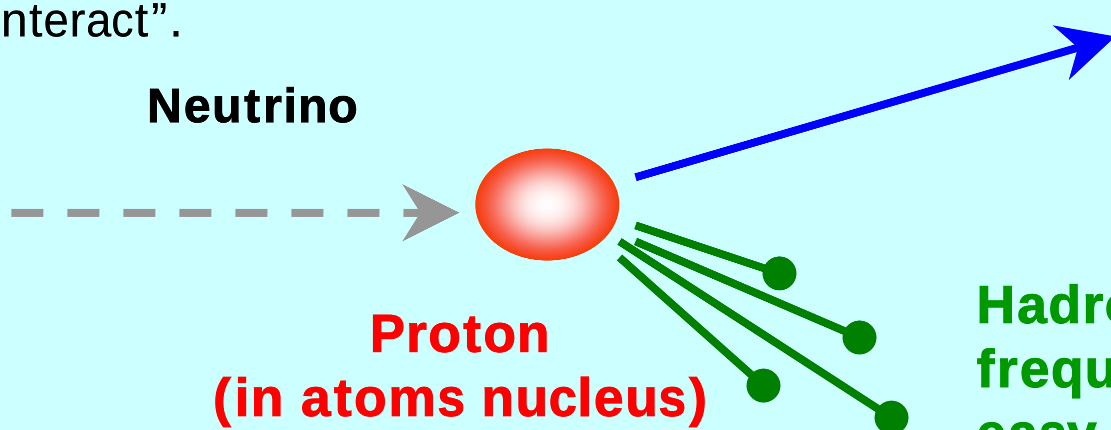
Physicists could not see how such an elusive particle could ever be detected...



Nobel Prize in Physics 1938

Experimental Detection of Neutrinos

In High Energy Physics, detection of a particle requires building a detector, which is a group devices in which particles will "do something" or in physics language will "interact".



Thousands of billions of solar neutrinos pass through our bodies every second!!

(we do not notice them because they interact very very very rarely)

1 out of 1,000,000,000,000 solar neutrinos would be stopped on its way through the Earth

Conclusion : In order to "see" (observe) Neutrinos we need huge detectors and a large number of them (neutrinos) !!!

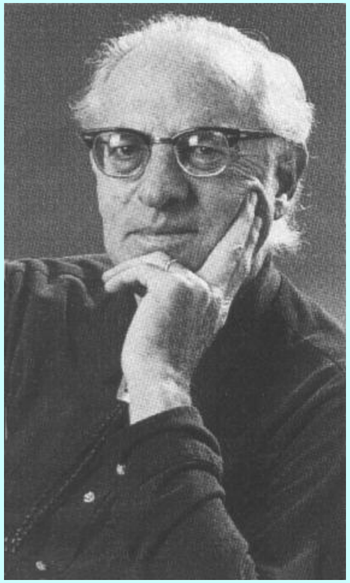
First Experimental Observation of the elusive neutrino

- In 1956 American Physicists F. Reines and C. Cowan performed an experiment close to the nuclear plant of Savannah River, South Carolina.

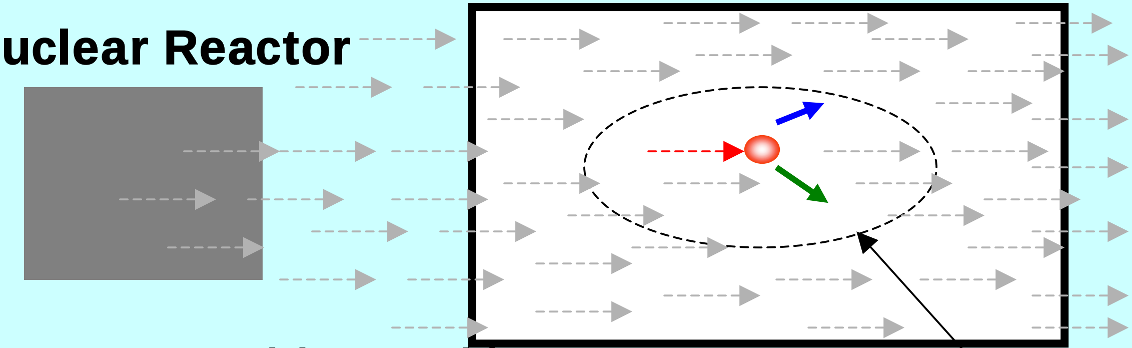
10000000000000 neutrinos per second per cm^2

They were expecting 2-3 interactions per hour !

Reines and Cowan succeeded in their attempt to prove the existence of the neutrino as a free particle almost 30 years after the neutrino was "born"



Nobel Prize in Physics 1995



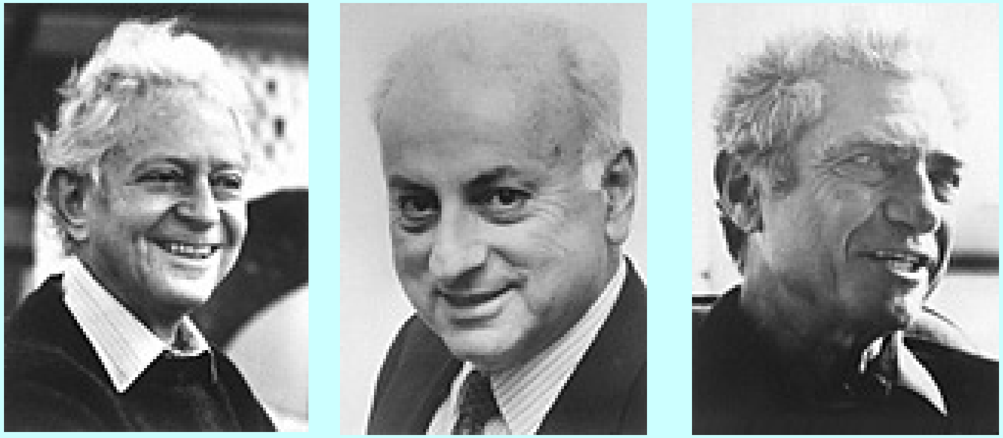
Is this the end of the neutrino story ???

- **1930 Neutrino is “born” by W. Pauli (Nobel Prize but not for that)**
- **1933 Neutrino is “baptized” by E. Fermi and the theory of weak interactions is formed. (Nobel Prize)**
- **1960 Neutrino is first observed experimentally by F. Reines and C. Cowan (Nobel Prize)**

<u>Is this the end of the neutrino story ???</u>

Nature, as you will see, would not share the same opinion, and neither did a group of Physicists at Columbia University ....

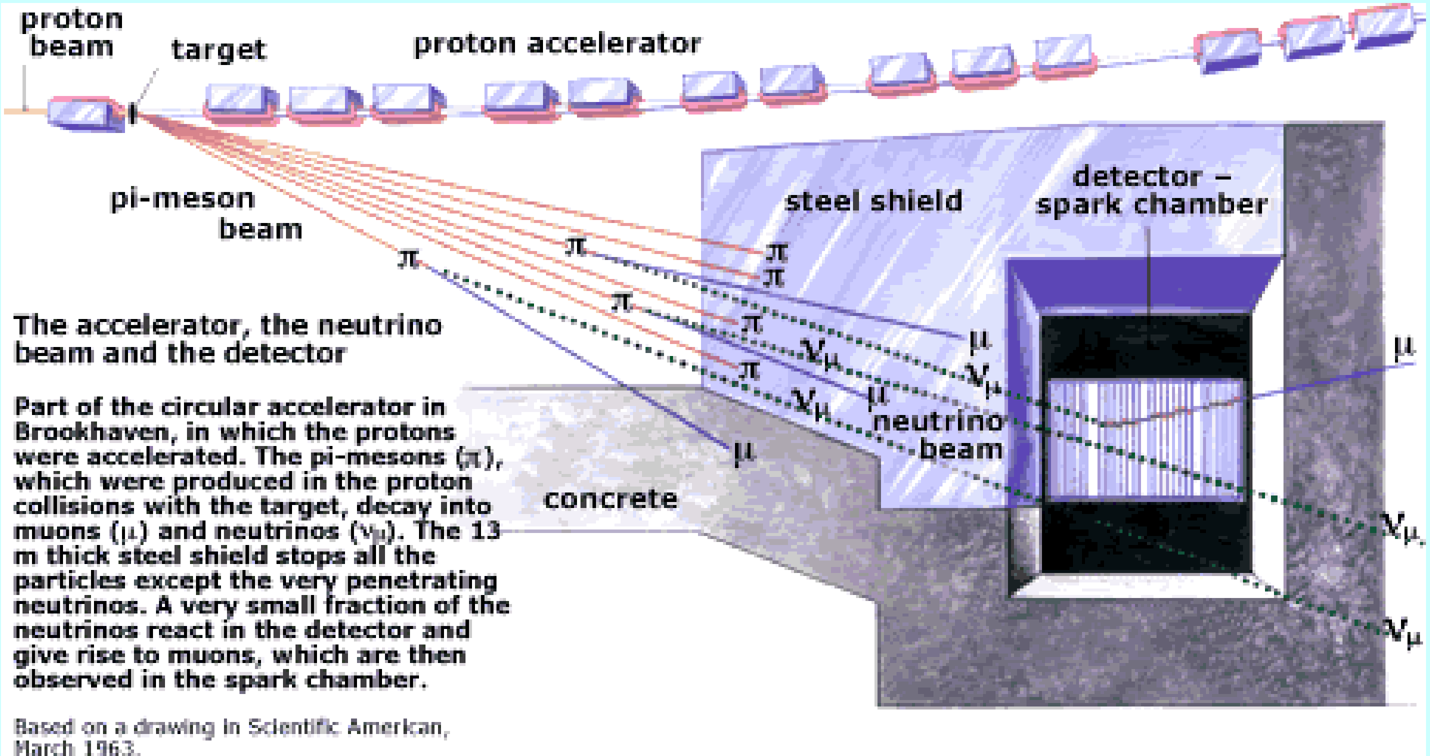
Hunt for yet another "type" of neutrino:the muon neutrino



The very first experiment using a beam of high-energy neutrinos

(1962) They experimentally discovered the existence of yet another neutrino pairing with the muon.

Nobel Prize in Physics 1988



Summary of the Press release for the 1988 Nobel Prize

Summary

The work now rewarded was carried out in the 1960s. **It led to discoveries that opened entirely new opportunities for research into the innermost structure and dynamics of matter. Two great obstacles to further progress in research into weak forces - one of nature's four basic forces - were removed by the prizewinning work.**

One of the obstacles was that there was previously no method for the experimental study of weak forces at high energies. The other was theoretically more fundamental, and was overcome by the three researchers' discovery that there are at least two kinds of neutrinos. One belongs with the electron, the other with the muon. The muon is a relatively heavy, charged elementary particle which was discovered in cosmic radiation during the 1930s. The view, now accepted, of the paired grouping of elementary particles has its roots in the prizewinner's discovery.

Solar Neutrinos (electron neutrinos)

J. Bahcall 1964

Nuclear interactions at the centre of the Sun produce :

HEAT – LIGHT - NEUTRINOS

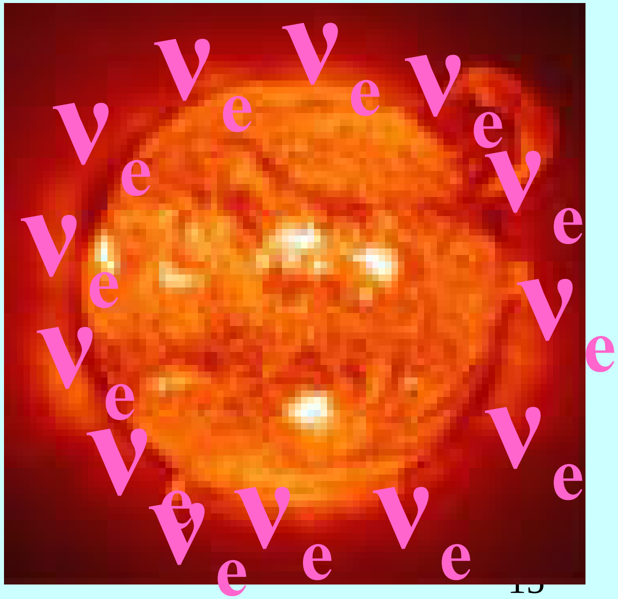
" Only neutrinos, with their extremely small interaction cross section can enable us to see into the interior of a star…"

He predicted theoretically the number of neutrinos we expect to form the sun.

R. Davis 1964

Nobel Prize in Physics 2002

Based on Bachall's prediction and on Pontecorvo's proposed method of detecting them, R. Davis proposed an experiment to detect neutrinos from the Sun.



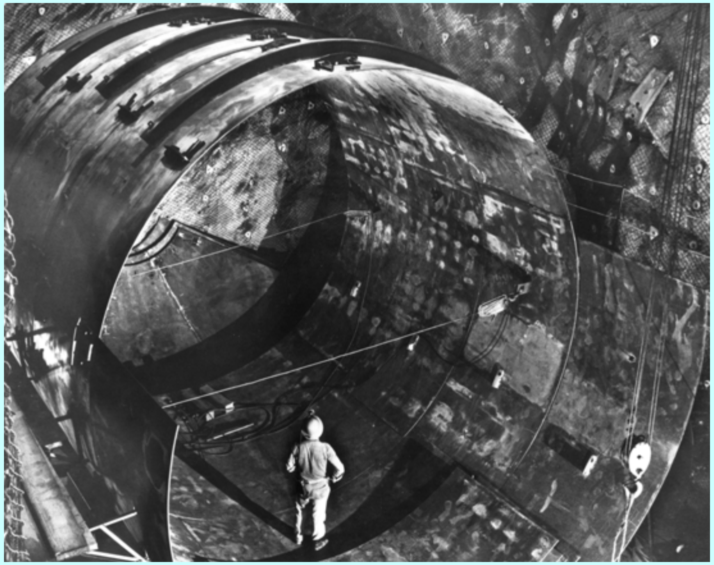
Homestake Experiment : the success and the birth of new "mystery"

- In the 1960s Davis placed a tank filled with 615 tones of the common cleaning fluid tetrachloroethylene in a gold mine in South Dakota, USA.

- **1968 : Davis experiment "sees" for the first time solar neutrinos, but much less than expected (about 1/3) !!!**

- **Where are the missing solar neutrinos??**

  (Neutrino was invented to solve a mystery and now it was creating one of his own!)



One step back : What did we know about "fundamental" particles in the early 1970's

- We knew that there were 4 leptons , and 4 quarks all grouped in "families".

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

- The whole picture was quite nice and symmetric (2 lepton families, 2 quark families)

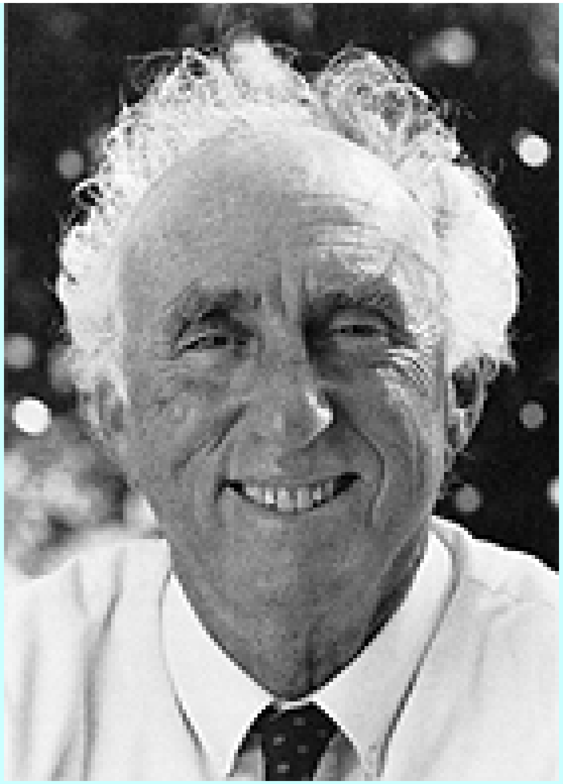
Yet another lepton : tau - the third one (possibly another neutrino?)

the muon, unknown heavier charged leptons. I dreamed that if one could find a new lepton, the properties of the new lepton might teach us the secret of the electron-muon puzzle.

Well, M. Perl's dream becomes true!

In 1975 he announces the existence of a new particle named **tau** from the **Greek word triton which means third** (name given by P.Rapidis who was then working with Perl)

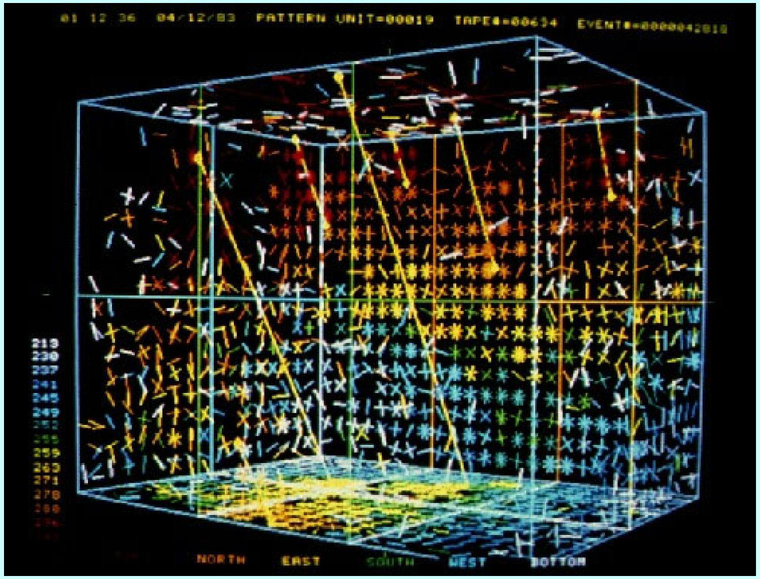
- Like the muon and the electron , the tau could also has its very own neutrino - the tau neutrino.



Nobel Prize in Physics 1995

Physicists – Miners and the atmospheric neutrino (muon neutrino)

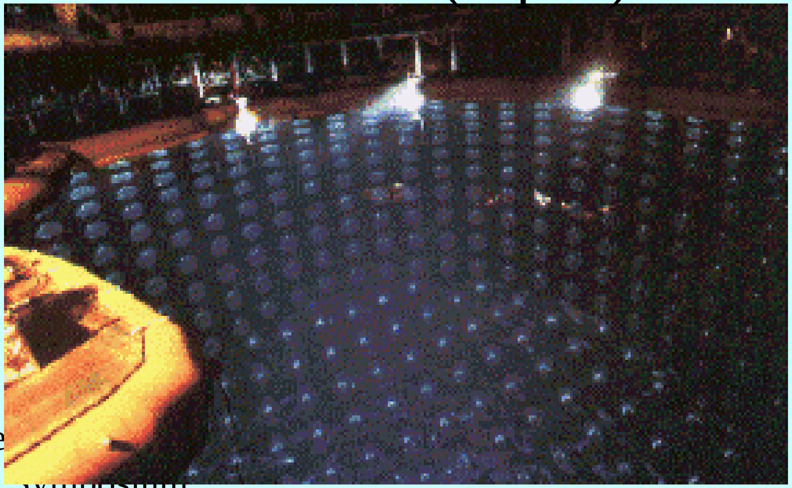
IMB (US)



GRAND UNIFIED THEORIES:

The driving force for large underground detectors (1980's)

Kamiokande (Japan)

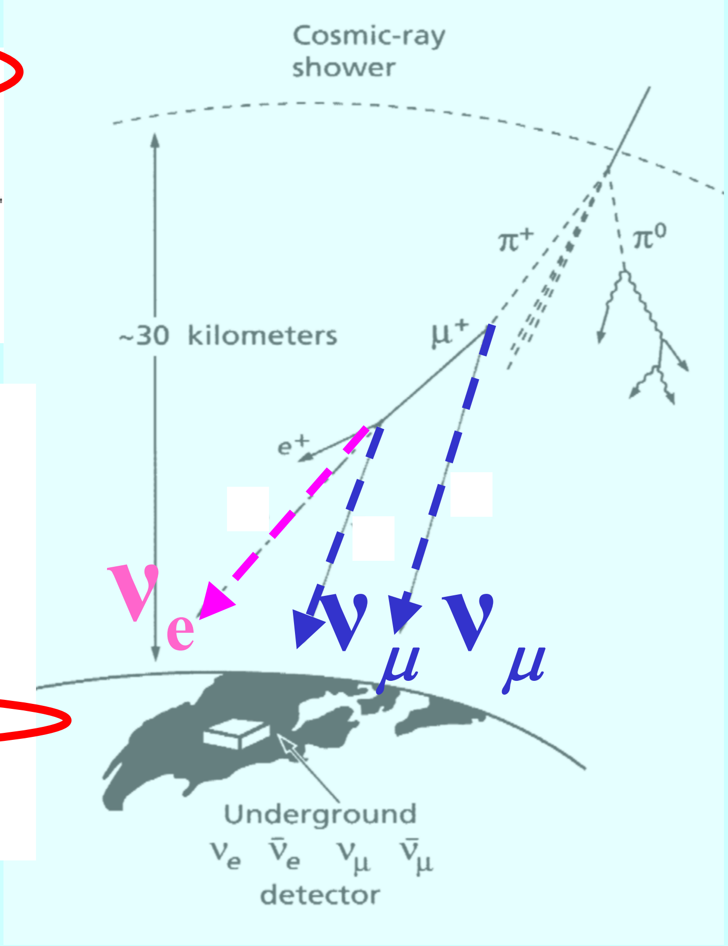


- **Neutrino interactions from neutrinos produced in the atmosphere were "the unwanted interactions" in these experiments.**

1986 : Atmospheric neutrino “anomaly”

26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν’s to electron ν’s in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any ef-

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single prong events is 59±7%(statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.



It is expected that the ratio of **muon-neutrinos** to **electron-neutrinos** is **2:1**.

The observation has a **shortfall** of **muon-neutrinos** with a ratio of about **1.3:1.**

Where are the missing (muon) neutrinos?"

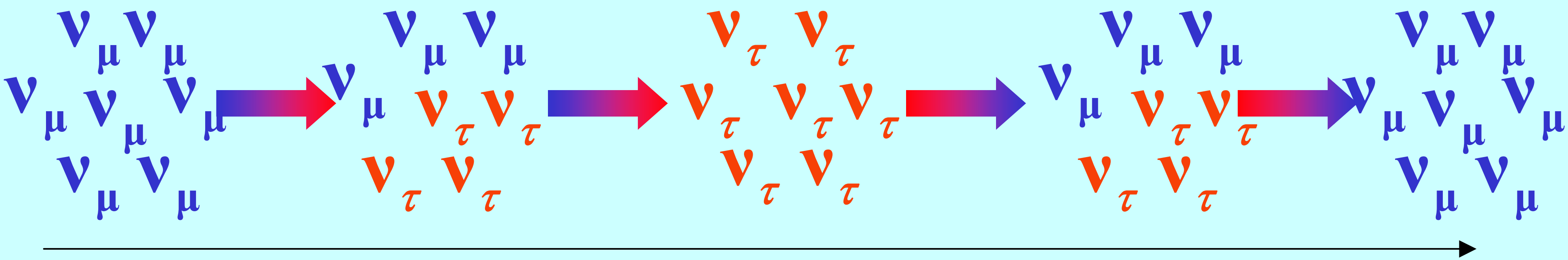
Striking (crazy?) theories about neutrinos : “Neutrino personality disorder”

- If neutrinos had a serious personality disorder, they could begin i.e as electron neutrinos, change into muon neutrinos as they travel, and then change back…and vice versa.
- The origin of the personality disorder is a quantum mechanical process, called "neutrino oscillations."
- Neutrino oscillations were first hypothesized by Bruno Pontecorvo in 1957, and independently by Z. Maki, M. Nakagawa and S. Sakata from Nagoya, Japan in 1962.
- There was no strong theoretical or experimental motivation for oscillations to occur, but it seemed it was not forbidden by any known rules.

Neutrino oscillations :

Tiny mass makes Big difference

Neutrino Source



Distance L

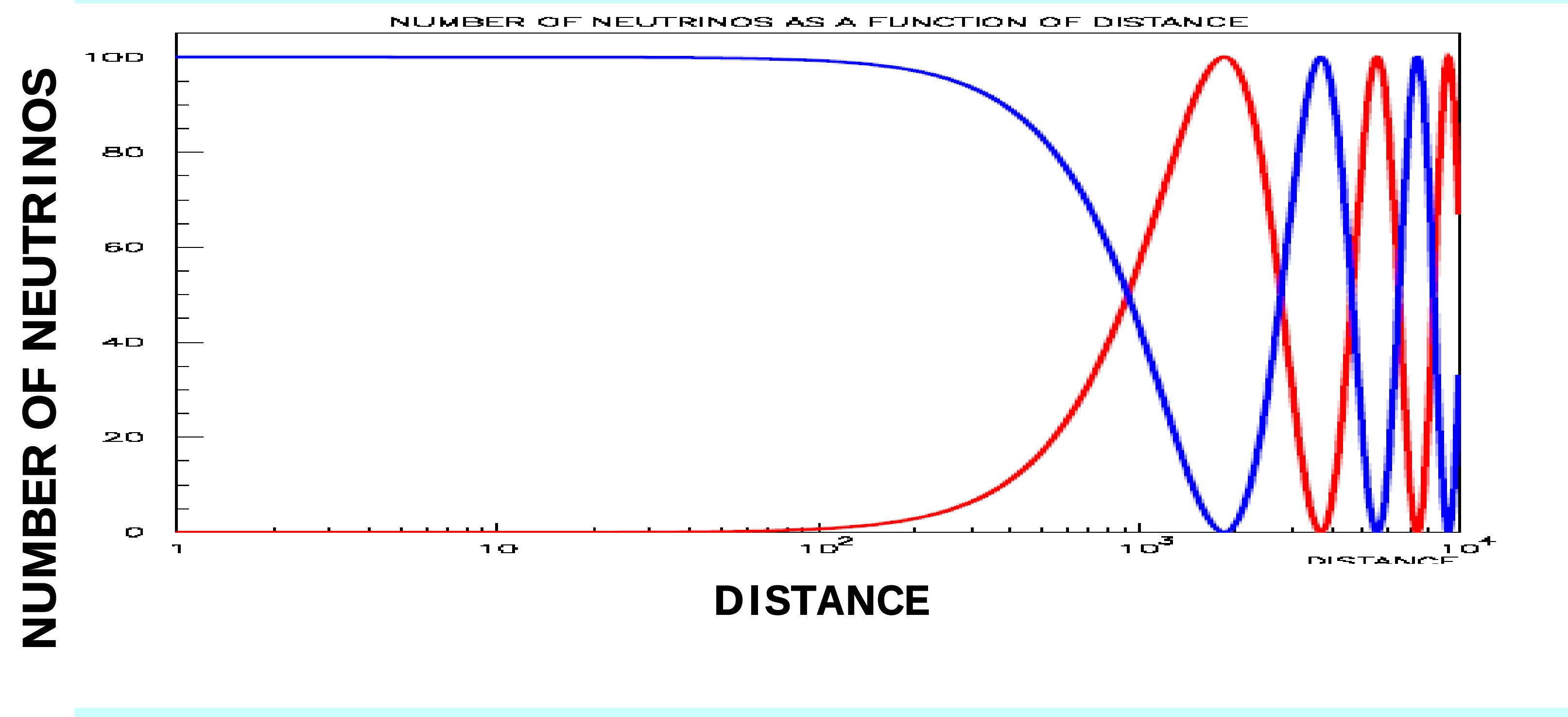
Neutrino oscillations in Math language

$$P = \alpha \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2 \cdot L}{E}\right)$$

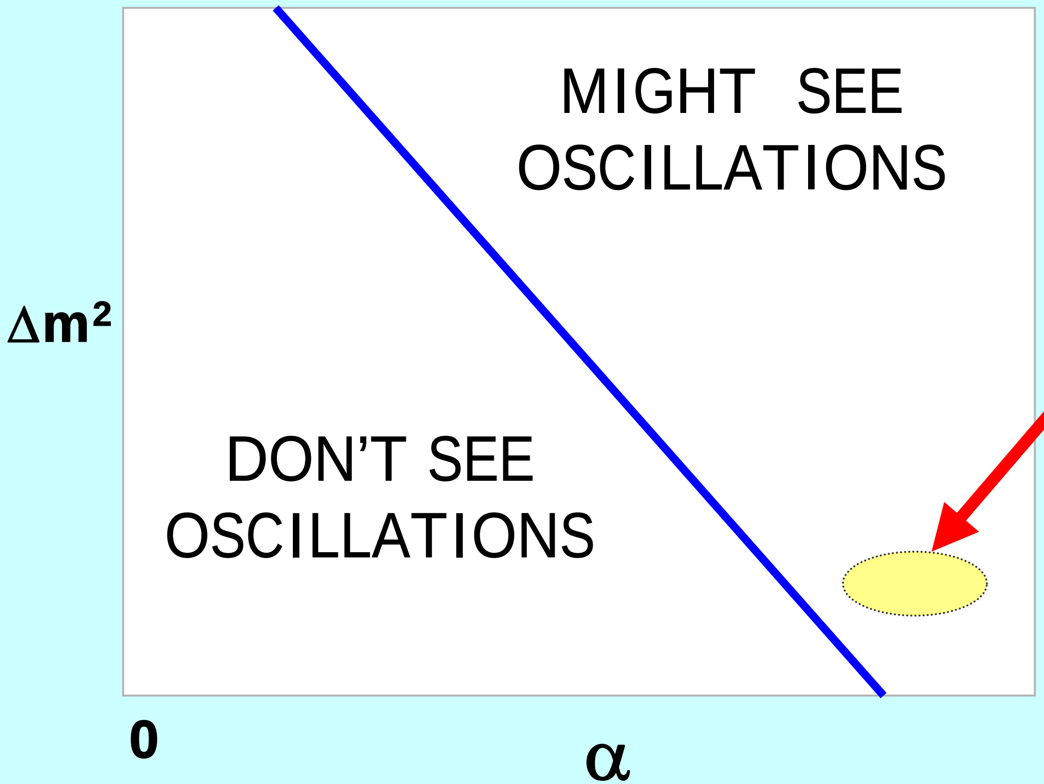
2 parameters we don't know and we want to measure

L: distance from source

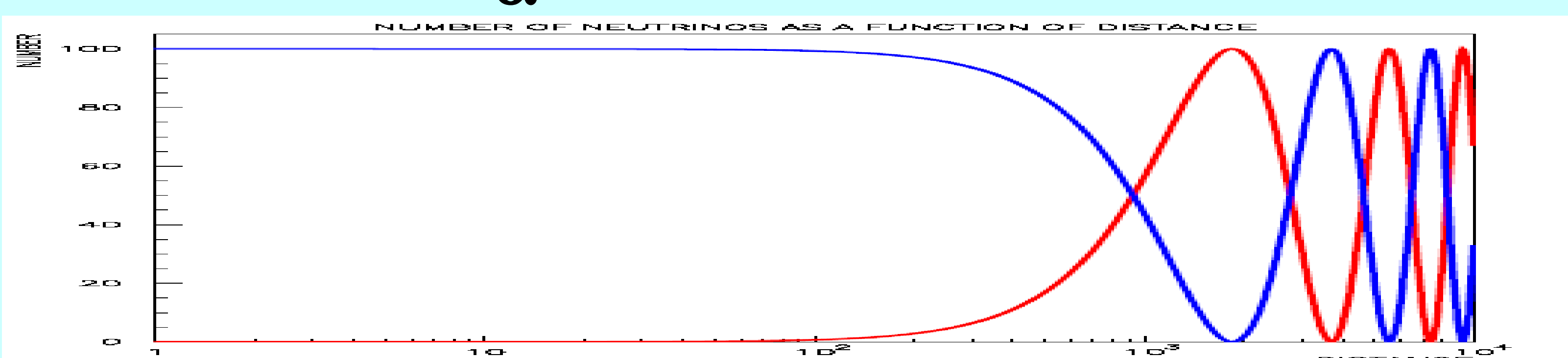
E: energy of neutrinos



Neutrino oscillations graphical answers



If experiments see oscillations then they report the value of Δm^2 and α with an error.



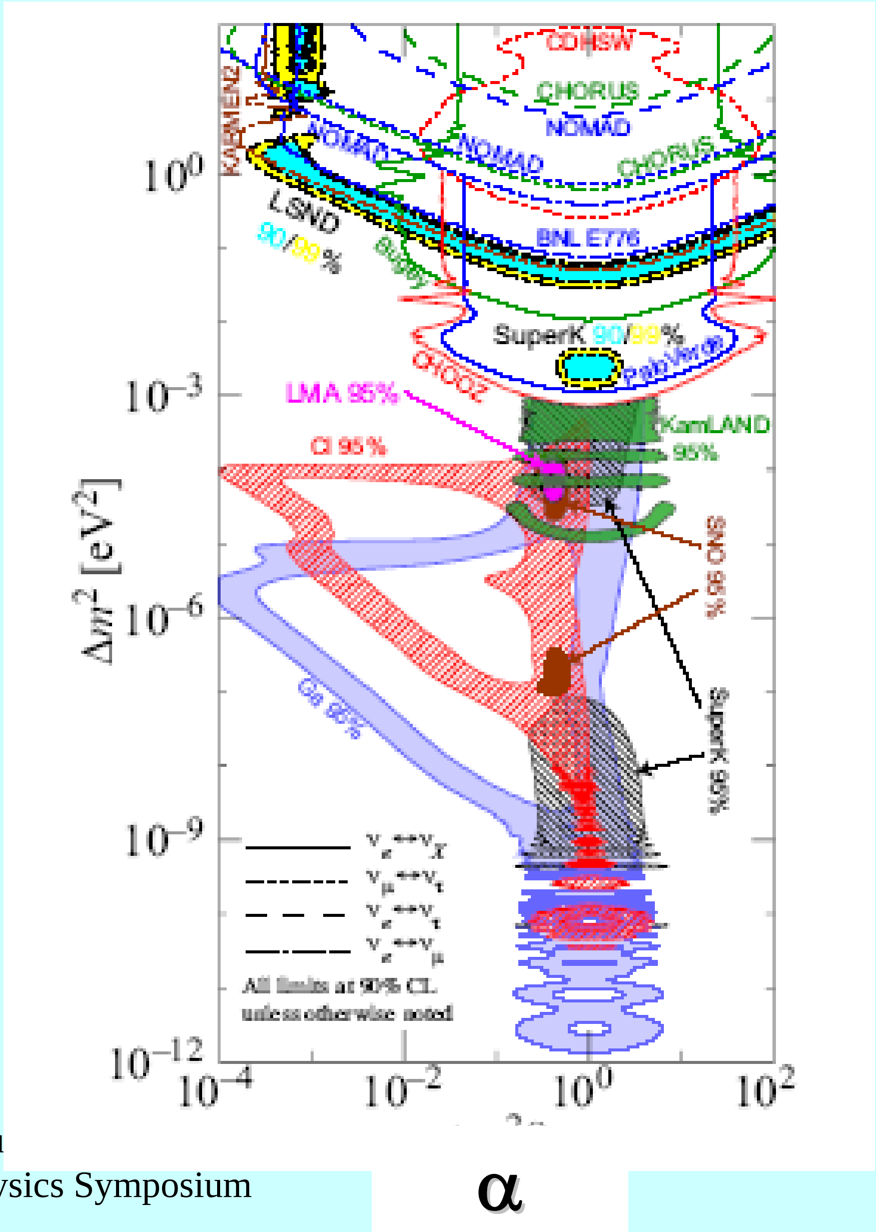
Neutrino oscillation experiments : 2D Graphs with “answers” on Δm^2 and α

1978 – 2002 many experiments searched for neutrino oscillations with either man-made “accelerator” neutrinos or man-made reactor neutrinos.

None of those “saw” neutrino oscillations.

BNL E704
CCFR
CDHS
CHARM
BEBC
BNL E775
BNL E776
NOMAD
CHORUS

Krasnoyarsk
Gosgen
Karmen
Bugey
CHOOZ
Palo Verde

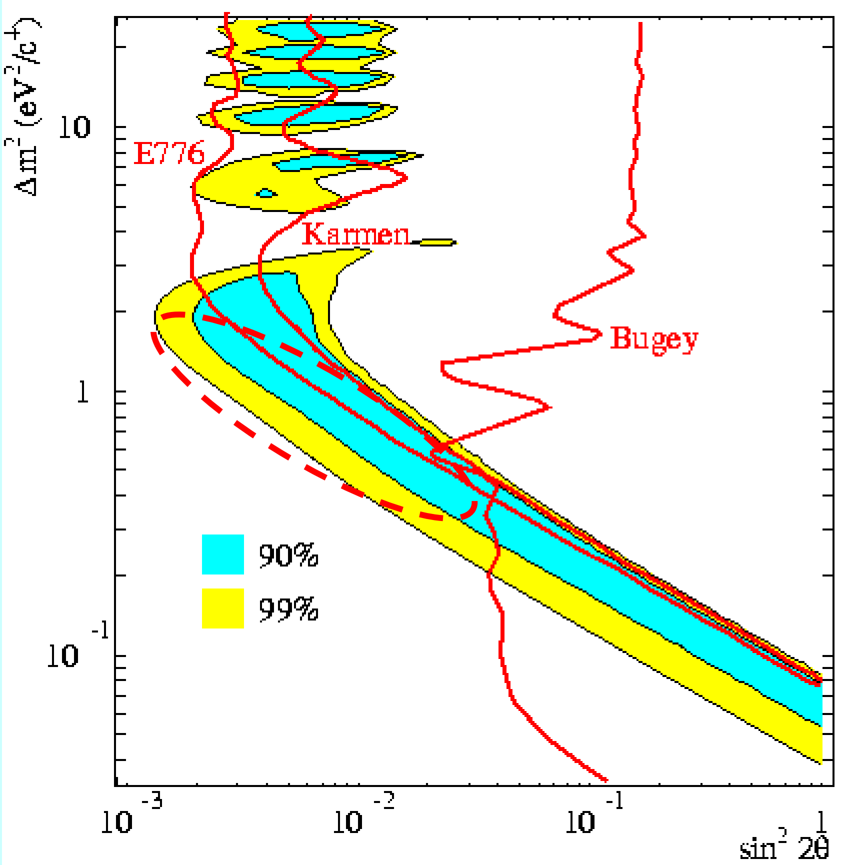


LSND Experiment (Los Alamos)

- In 1996 LSND experiment announce the evidence of neutrino oscillation, in a quite "unfortunate" region...

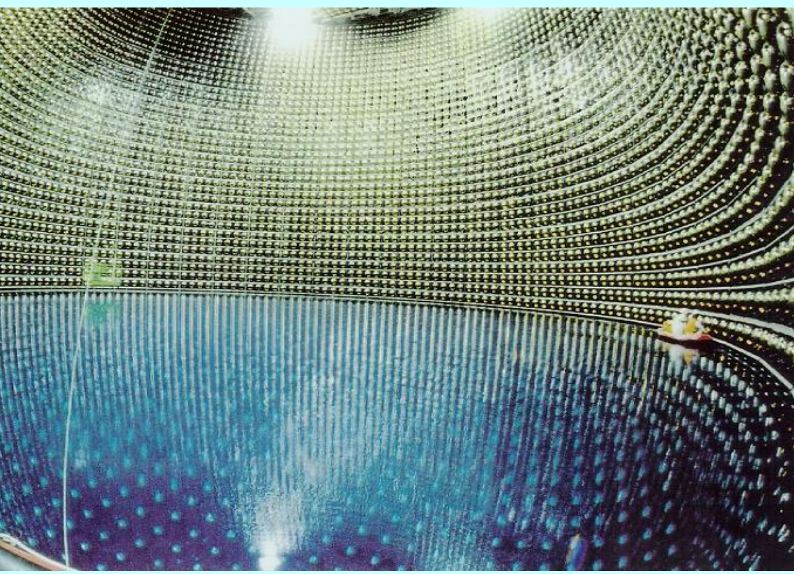
- **In order for such oscillations to occur there must yet another neutrino , different than the already seen 2 and predicted 3 called the sterile one...**

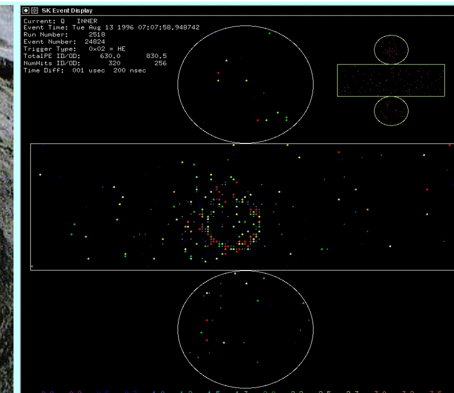
- **How many neutrinos are there?? ANOTHER PUZZLE TO BE SOLVED!!**

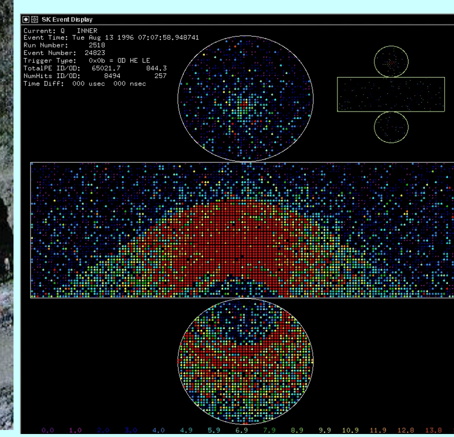


1998 Super Kamiokande (Japan)

We present an analysis of atmospheric neutrino data from a 33.0 kiloton-year (535-day) exposure of the Super–Kamiokande detector. The data exhibit a zenith angle dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino flux. Experimental biases and uncertainties in the prediction of neutrino fluxes and cross sections are unable to explain our observation. The data are consistent, however, with two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at 90% confidence level.

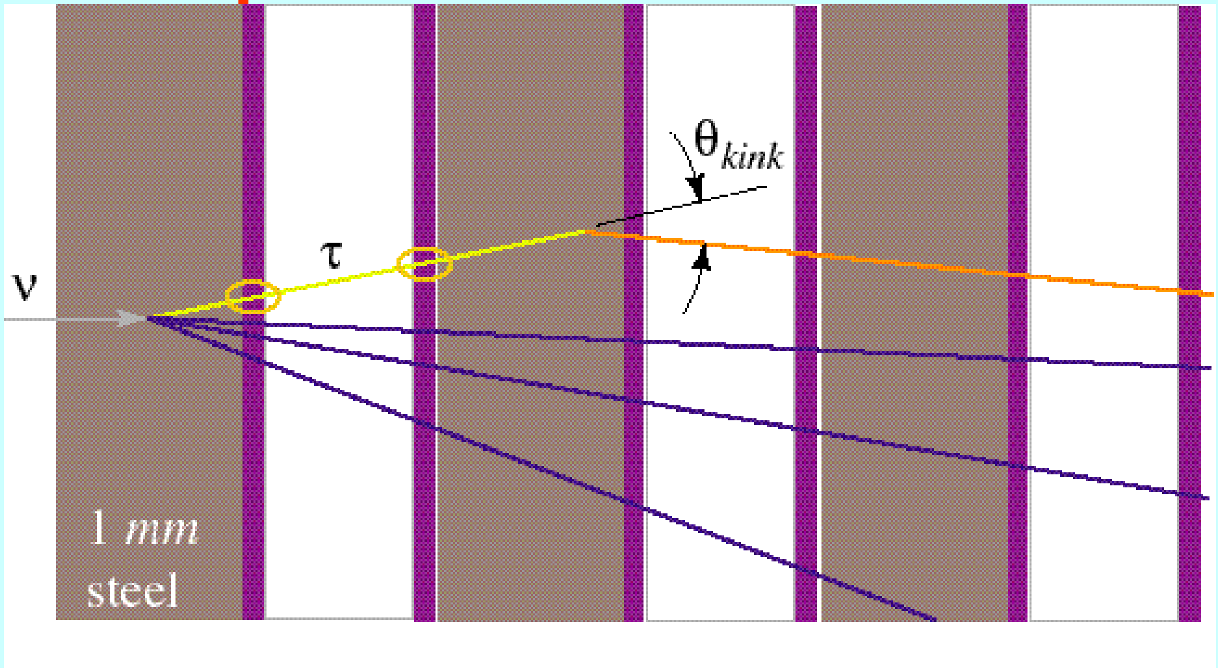






2000 : DONUT (Fermilab) (The third "tau" neutrino is definitely there)

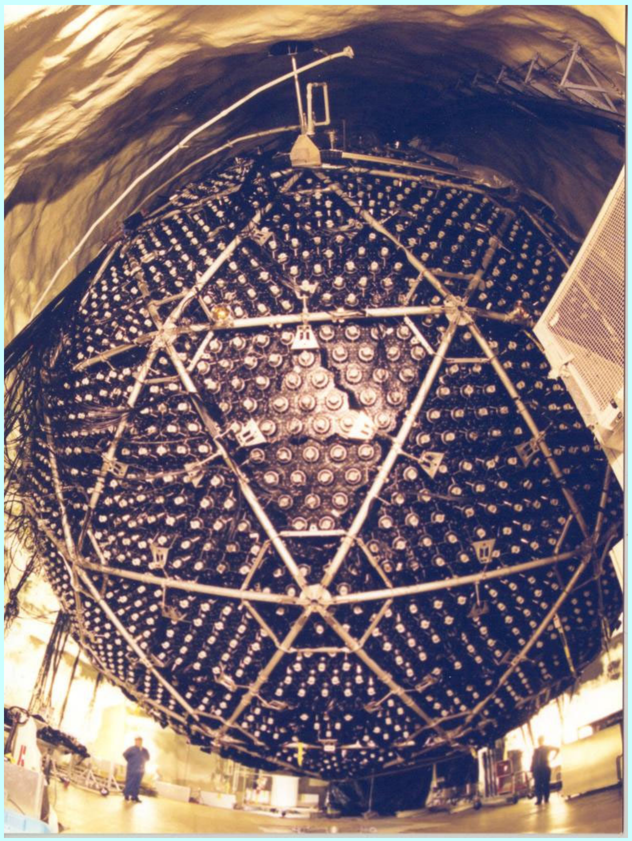
In the year 2000 the DONUT collaboration announced the first direct observation of the tau neutrino 25 years after the discovery of the tau lepton!



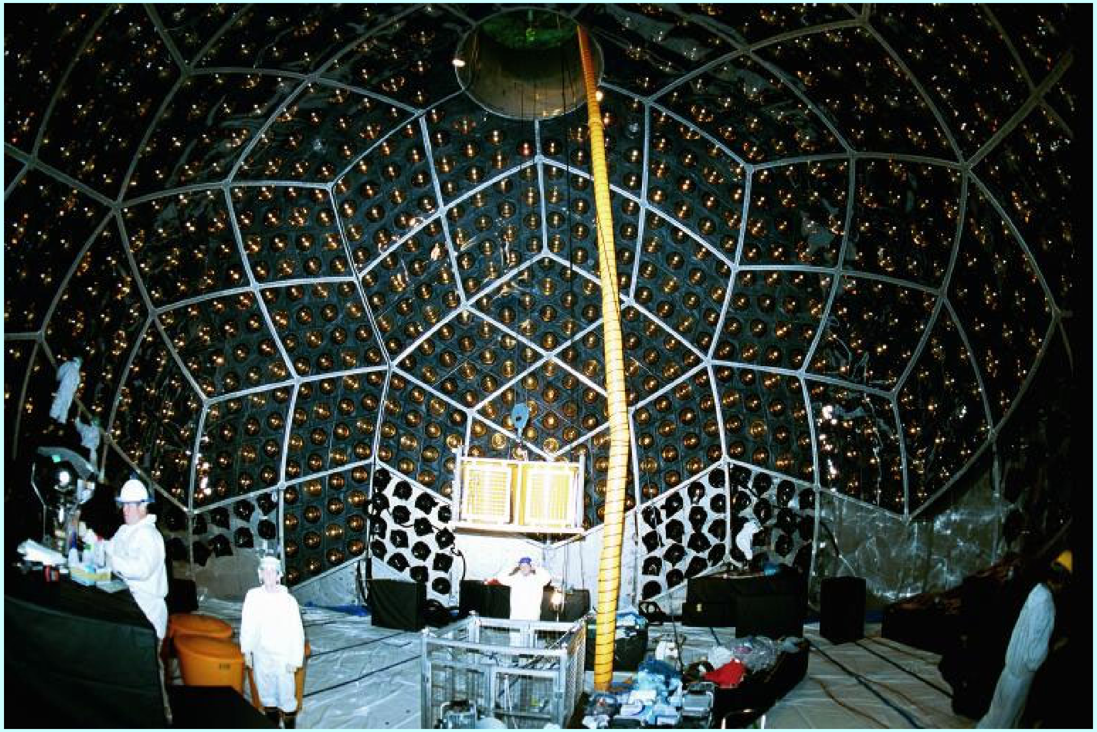
2001 SNO (Canada) : The solar neutrino anomaly is indeed an "anomaly"

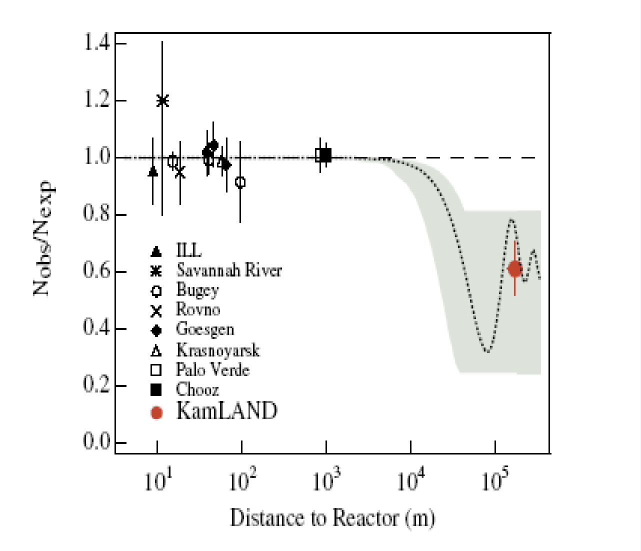
They confirm the Solar Neutrino "anomaly" 30 years after is was first observed (Davis and Bachall) and made measurements that give confidence that the Solar Model (**J. Bahcall**) is PRECISE!!

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty, for 33 years, people have called into question my calculations on the Sun."



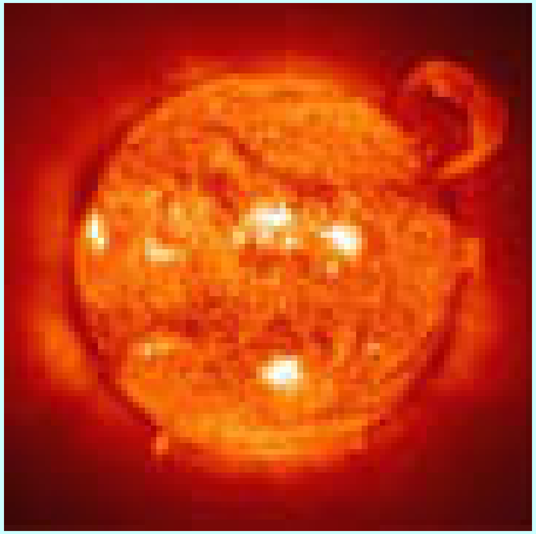
2002 KamLAND (Japan) : man-made electron neutrinos oscillate…





First experiment ever to observe neutrino oscillations with man-made electron neutrinos !!!

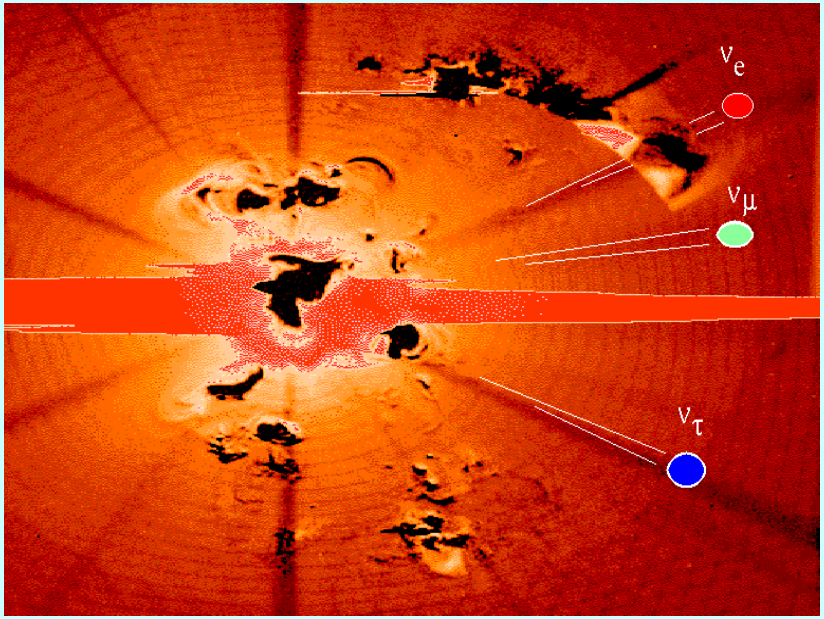
What have we learned so far …



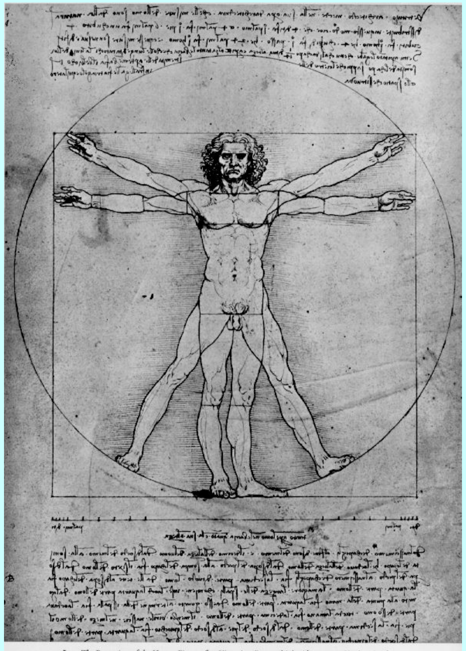
Sun emits :

Neutrinos exist and they are everywhere!

2000000000000000000000000000000000000000 per second!



Big Bang : 300 neutrinos per cm^3 !



Our Body : 4000 neutrinos per second!

…

Since the neutrino "birth" in 1930 what we have learned 75 years later is a lot:

There are at least 3.

They must have tiny but non zero mass

Atmospheric (muon) neutrinos oscillate.

Solar (electron) neutrinos oscillate.

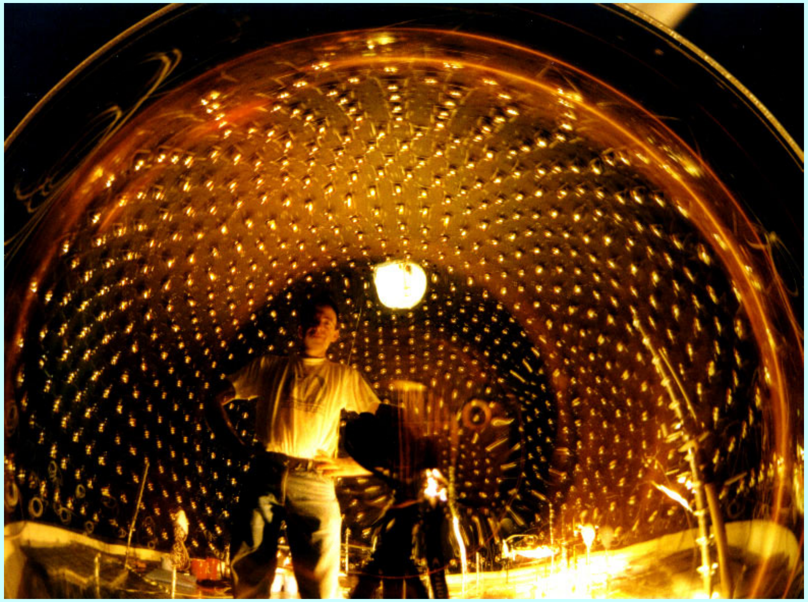
What are we trying to learn as we speak !

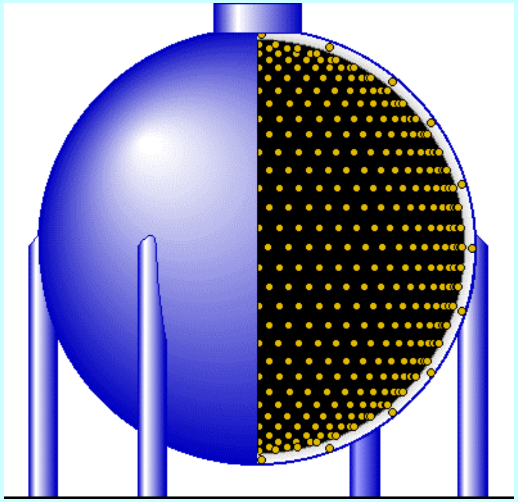
Are there really 3 altogether or more? (Remember LSND and "sterile" neutrinos) ← MiniBoone

Do man-made muon neutrinos oscillate and what are the precise oscillation parameters? ← K2K & MINOS

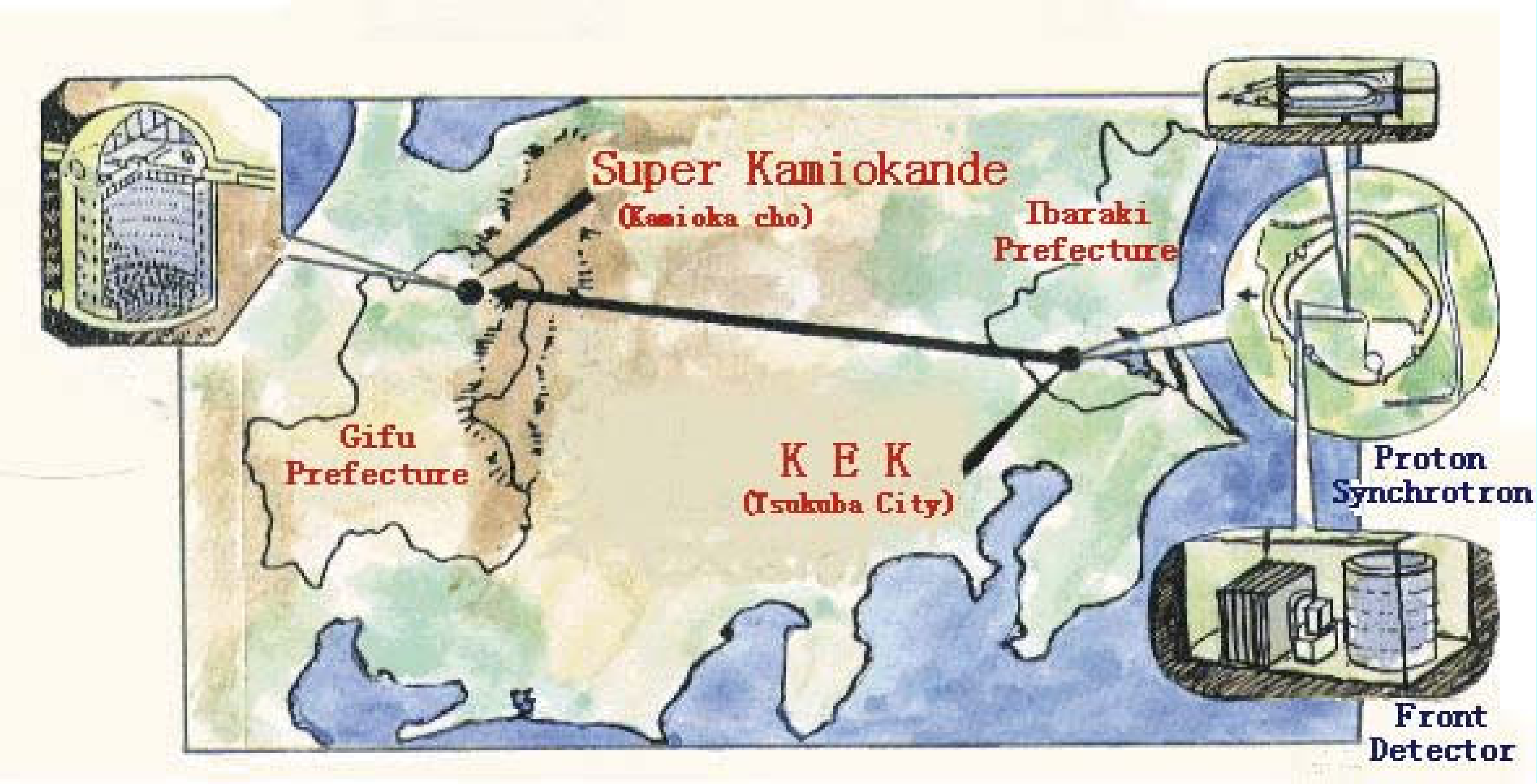
MINIBOONE (Fermilab)

- Started taking data 2002 with an aim to check LSND results
- If MiniBoone confirms LSND “all hell will break loose”!
- MiniBoone will tell us the answer soon (end of this year –early next year) !





K2K (Japan)



- First long baseline experiment to study neutrino oscillations using man-made muon neutrinos.
- Results are consistent with Super Kamiokande (not all muon neutrinos make it to the second detector preserving their identity!)

MINOS (Fermilab)

- MINOS is a two detector long baseline neutrino oscillation experiment.
- Started taking data in March of this Year.
- Using the most intense neutrino beam ever!
- The neutrino beam is traveling 456 miles before we measure it again !!

Why are we here??

- There is a small problem in the universe: matter. The stars, planets everything (including ourselves) are all made of the matter.

- However , the universe should contain no matter at all. It is believed that during the Big Bang, 14 billion years ago, equal amounts of matter and antimatter were created.

- Given our current knowledge, soon after that matter and antimatter should have annihilated leaving behind a could of photons and nothing more.

- But we know beyond any doubt that this was not the case!! (hence our being here today)...

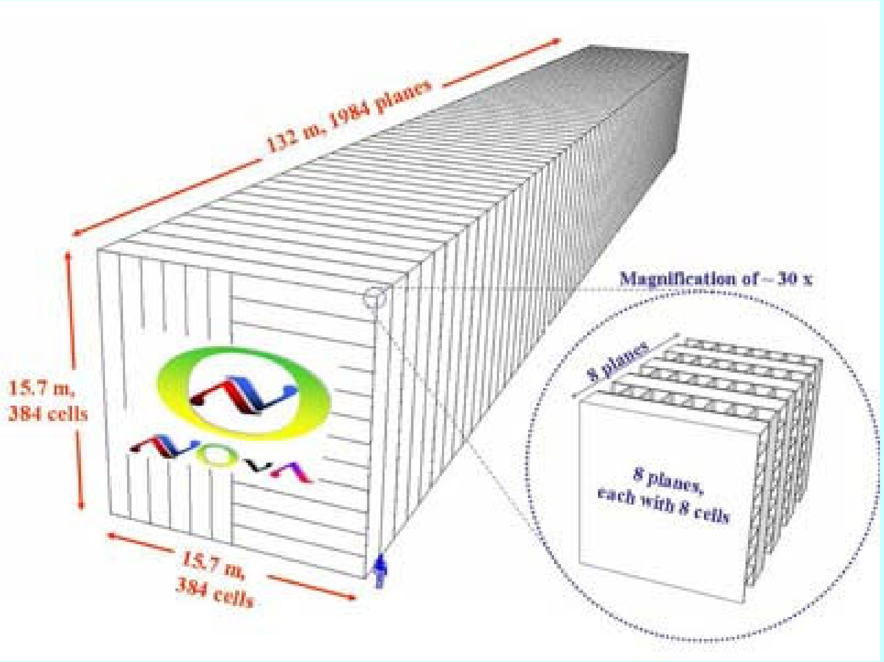
- CP violation - an obscure effect seen only with certain kinds of elementary particles - could provide the answer.

WHAT DON'T WE KNOW SO FAR

- Do neutrinos violate CP ? (NOVA and TK2)
- Which neutrino is the heaviest one? (NOVA)
- What are the neutrino masses ?
- Are neutrinos their own anti-particles?

NOVA (Fermilab)

- NOVA is a future neutrino experiment proposed at Fermilab (and approved) .
- **The NOVA detector is going to be 30,000 Tons of liquid scintillator !!!**
- Neutrinos will travel from Fermilab ~ 500 miles to Northern Minnesota.



NOVA LENTGH = 1.5 FOOTBALL FIELDS

NOVA (primary) GOALS

Measure CP violation in the neutrino sector

Determine which neutrino is the heaviest one

T2K (Japan)

T2K (primary) GOALS

Measure CP violation in the neutrino sector

NOVA & TK2

Best Measurements and discovery potential will come from combination of TK2 AND NOVA!!

"But only the one who dare can win"

- Neutrinos were "invented" in a crisis as a desperate attempt to save one of Physics most important Laws : the Energy Conservation Law.

- Since their "birth" they have been full of surprises and controversies : although they have helped us so far understand fundamental particles and how they interact, they have, in the same time proven, with their strange behavior, that our current best Models of understanding the laws of nature are incomplete.

- There are many questions (some having to do with the understanding of the Universe and our very own existence) involving neutrinos still waiting for answers...

- ***Therefore, having in mind Pauli's suggestion "But only the one who dare can win" we ought to try and understand their properties and interactions the best way we can!***